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STUDY OF OPEN JET WIND TUNNEL CONES

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Summary

Tests have been made by the National Advisory Committee for Aeronautics on the air flow in an open jet wind tunnel with various sizes, shapes, and spacings of cones, and the flow studied by means of velocity and direction surveys in conjunction with flow pictures. It was found that for all combinations of cones tested the flow is essentially the same, consisting of an inner core of decreasing diameter having uniform velocity and direction, and a boundary layer of more or less turbulent air increasing in thickness with length of jet. The energy ratio of the tunnel was obtained for the different combinations of cones, and the spilling around the exit cone causing undesirable air currents in the experiment chamber was noted. An empirical formula is given for the design of cones having no appreciable spilling.

Introduction

The importance of having a smooth and uniform flow in a wind tunnel is well recognized. The flow in tunnels has been studied in various ways, including velocity surveys made with both Pitot tubes and anemometers, surveys of direction of air flow by means of yawmeters, and pictures of the flow. In 1909, Riabouchinsky obtained pictures of the flow in an open jet tunnel by inserting a thin plate in the jet horizontally, dividing the flow into equal upper and lower sections. The plate was surfaced with a gummed black paper upon which lycopodium powder was sprinkled, and the black showed through where the powder was blown off. Better results have been obtained at the Langley Memorial Aeronautical Laboratory with a method developed in this country using a mixture of lamp black and kerosene painted on the plate, and this method was used to obtain flow pictures in the tests described in the present report. These pictures do not represent the true flow for the lines of flow of the liquid on the plate are of course affected by surface conditions. However, while not always indicating the true direction, they are quite consistent in showing the region of flow and the velocity differences correctly.

Surveys of velocity and direction were also made with Pitot tube and yaw head and checked against the flow pictures. In addition, the energy ratio was determined as a measure of the efficiency of the various combinations of cones. These include different shapes and diameters of entrance and exit cones, various distances between cones, and various amounts of flare on the exit cone. The effect of bleeder holes in the flare of the exit cone was investigated also.

Apparatus

The N.A.C.A. 6-inch auxiliary wind tunnel at the Langley Memorial Aeronautical Laboratory was used for these tests. It is shown with its standard cones in Fig. 1. The entrance cone, it will be noticed, has a detachable cylindrical extension, 6 inches in diameter and 8 inches long. The exit cone also has a cylindrical portion back of the bell, which is telescopic and allows the distance between the cones to be adjusted. The tunnel is of the return passage type, having guide vanes at the corners and a honeycomb at the large square section of the entrance cone. The air is driven by a centrifugal blower run by a direct current motor.

In addition to the regular cones, which are of Eiffel type, three special entrance cones and two exit cones were built of sheet metal and wood, the portion near the jet being turned to shape from wood in a lathe. The shape of these experimental cones is shown in Fig. 2. It will be noticed that the entrance cones have a rather large reduction of area in a comparatively short distance, and that they all are identical excepting for the mouths which are brought up to different diameters. Entrance cone A has at the mouth a diameter of 6.82 inches. Entrance cone B has 3/4 the area of A at the mouth, and C has 1/2 the area of A. Exit cone E has the same diameter at the throat as entrance cone A, while exit cone D has a diameter 1/4 greater at the throat. The bells of the exit cones are made of 1-inch layers of wood which can be removed layer by layer to give various amounts of flare.

For obtaining the flow pictures a metal plate painted white was put in the center of the jet horizontally between the two cones, parallel to the air stream. A mixture of lamp black and kerosene was then applied to the top surface of the plate with a paint brush and the tunnel started and brought to speed as quickly as possible. After about a half minute of running at constant speed, when the flow picture had become well defined and fairly dry, the tunnel was shut down and a photograph taken of the picture.

The ratio of the kinetic energy of the air at the mouth of the jet to the electrical energy input was found for each case tested as a measure of the efficiency of the tunnel. In calculating the kinetic energy the velocity of the air was considered constant over the entire area of the mouth of the entrance cone. A voltmeter and ammeter were used for getting the electrical input power.

Typical Open Jet Flow

A typical flow picture is shown in Fig. 3, with a diagram of the velocity and direction across three sections superimposed upon it, as obtained from Pitot tube and yaw head held in the diametral flow plane with the painted plate removed. The outstanding feature of the picture is that it shows two distinct regions of flow; an inner core of smooth rapidly moving air in the form of a converging cone, and an outer diverging cone of more or less turbulent air. All of the flow pictures taken for the various types and combinations of cones have the same general appearance, and the angle of convergence of the inner core is constant for all cones and speeds, its value for the included angle being about 9°. The arrows on the diagram show the direction of flow as obtained by means of the yaw head. These show that although the periphery of the central cone is tapered, the direction of flow has no general convergence but is substantially straight and uniform within about 1°. The length of the arrows is a measure of the velocity of the air, and the dot and dash lines show the variation of the velocity across each section. At all points within the inner cone the velocity is constant within the experimental error (about one-half of 1%). For this particular flow picture it is 102.5 M.P.H. At the edges of the inner cone the velocity begins to fall off and is practically zero at the outside of the outer cone. The direction of flow, it will be noticed, is outward or diverging throughout all of the outer turbulent region, this divergence even extending for a short distance into the region of constant velocity. It will be noticed that the direction of flow is not always easily detected from the lines on the flow picture. The divergent flow at the sides, for instance, is not clearly indicated by the picture within the region of constant velocity.

In general, however, the direction is shown approximately, and the change of velocity at the edges is shown quite definitely. Just in front of the exit cone bell, the picture indicates a transverse flow, or spilling over of the air. This spilling is the cause of undesirable air currents in the experimental chamber which vary in strength for different cone designs.

The fact that the flow is substantially the same with all combinations of cones and that the angle of convergence is constant, leads to the idea that this convergence is practically independent of the shape or relative size of the cones within the limits of these tests. It probably depends, as suggested to the writer by Mr. Orville Wright, entirely on the viscosity of the air, and is, in fact, a measure of the viscosity.

The conception of the flow then is that of a jet of air moving with uniform velocity and direction, which is constantly becoming smaller in diameter as it proceeds due to the friction at the edges. This friction reduces the velocity of the air at the outside of the jet, causing the outside or over-all diameter of more or less turbulent air to increase as it proceeds. The cone of air having uniform velocity has a diameter of 85% to 90% that of the entrance cone at the small end or mouth of the cone and is reduced as it goes downstream, the included angle of its sides being approximately 9°. At a distance downstream equal to the diameter of the entrance cone, the core of air having uniform velocity has about 3/4 the diameter of the entrance cone.

Effect of Varying Velocity

Two sets of cones, those belonging to the 6-inch tunnel and the combination of entrance cone A and exit cone D, were run at three different speeds each, and a flow picture and a velocity survey made for each case. No difference in the flow can be detected from pictures or velocity surveys for the various speeds. The energy ratio for the tunnel with its standard 6-inch cones as shown in Fig. 1, is .41 for the high and medium speeds (102.5 and 81.5 M.P.H.) but falls off to only .22 at the low speed (51.6 M.P.H.) probably due largely to a decrease in the efficiency of the centrifugal fan. At 102.5 M.P.H. the tunnel with cones A and D has an energy ratio of .64, which is 56% better than that for the standard 6-inch cones. The low efficiency of the standard cones can be accounted for by the very large diverging angle of the exit cone just in front of the blower. At 81.6 M.P.H. the energy ratio with cones A and D falls off slightly to .60 and at 51.6 M.P.H. it drops to .29. It is probable that most of this change of energy ratio with speed is due to change in the centrifugal blower efficiency which would be largely eliminated by the use of a propeller fan. Furthermore, a good propeller fan would have about twice the efficiency of the centrifugal blower, thereby doubling the energy ratio of the tunnel and putting it within the range of average tunnels, the energy ratios of which vary from about 1.00 to 2.00.

Distance between Cones

The standard cones for the 6-inch tunnel are arranged so that the distance between the cones, or in other words the length of the jet, can be adjusted. As can be seen from Fig. 1, the exit cone has a telescopic cylindrical portion, and the entrance cone has a detachable cylindrical extension. With this latter extension in place the distance between the cones was varied an inch at a time from 4-1/4 to 10-1/4 inches, and with the extension removed, from 10-1/4 to 18-1/4 inches. Thus the total variation was from .71 to 3.04 times the diameter of the mouth of the entrance cone. The energy ratio for the 10-1/4 inch spacing is the same with or without the cylindrical extension, and since it does not change the flow in the jet as shown by the flow pictures, it seems that cylindrical extensions on entrance cones are ordinarily quite useless. However, for these experiments it permits a wider range of distances between cones.

Fig. 4 shows how the energy ratio changes with length of jet. The change it will be seen is very slight; there being a drop of about 7% from a spacing of .7 the diameter of the entrance cone to three times its diameter. For spacings of about one and one-half diameters or less there is no appreciable spilling of the air outside of the exit cone, the flow being confined entirely to the space between the cones. As the spacing is increased, however, a noticeable amount of spilling occurs; at two diameters it is considerable, and at three diameters, excessive. The flow near the entrance cone is the same for all spacings, but at the exit cone as the spacing is increased, the diameter of the internal region of air having constant velocity reduces, and that of the outer turbulent region of slower moving air increases.

Relative Diameters of Entrance and Exit Cones

Each entrance cone of Fig. 2 was tried out with each exit cone, making in all six ratios of exit to entrance cone diameter ranging from 1 to 1.78. The flow in each case, as determined by flow pictures and Pitot velocity surveys, is similar to that given as typical in Fig. 3. The energy ratios and the amount of spilling, however, vary considerably. If the diameter of the exit cone is greater than about one and one-half times that of the entrance cone, there is no perceptible spilling with the spacing used in these tests. As the size of the exit cone is reduced with respect to that of the entrance cone spilling is noticeable, and it becomes very great when both cones are of the same size. Also, in this particular tunnel the flow fluctuates considerably more with time for the two cases having the lowest ratios of exit to entrance cone diameter than for the others.

The energy ratios for the various combinations are plotted in Fig. 5. The energy ratios for all cases having the small exit cone are in general less than those with the large cone, most likely due to the greater angle of divergence of the small cone just back of the bell. For each exit cone there is a ratio of cone diameters which gives the maximum energy ratio; this diameter ratio is about 1.2 for the small exit cone and 1.35 for the large. Of course, it must be kept in mind that in this particular tunnel a considerable portion of any change in energy ratio is due to change in blower efficiency, but it seems reasonable to assume that an exit cone about one-fourth larger in diameter than its entrance cone would have very nearly the maximum energy ratio.

One noteworthy feature brought out by these tests is the small increase in velocity that is obtained by reducing the diameter of the jet. The electric power input was kept the same for all cases and the velocity for each set of cones measured. With the large entrance and exit cones, A and D, the speed is 102.5 M.P.H. Reducing the area of the entrance cone to 3/4 its former value by substituting B for A, increases the speed to only 115 M.P.H. even though the energy ratio is a trifle better. With cone C having 1/2 the area of A, the velocity is but slightly greater (118.5 M.P.H. when the large exit cone is used, and 121.2 M.P.H. when the small exit cone is used). Although these increases in velocity with reduction in diameter appear small, they are entirely in accord with what is to be expected from theory, for if the energy ratio and power input remain constant, the velocity increases as the cube root of the decrease in area.

Exit Cone Flare

As previously stated the bell of the large exit cone, D, is built up of five layers each 1 inch thick, which can be removed one at a time to give various amounts of flare. The purpose of this flare is to eliminate spilling of the air, and the necessity for some sort of collector of large diameter can easily be appreciated after a glance at any one of the flow pictures.

There is a slight amount of spilling with cones A and D, even when all the layers of the exit cone are in place. This is not increased noticeably when one layer is removed, and only slightly with three layers removed. With four layers off, however, considerable air is spilled into the experiment chamber, and with all five off leaving the metal cone with no projection of any kind on the end, a large quantity of air is spilled. In the latter case the spilled air continues straight along the outside of the exit cone, while in all the other cases it is given a transverse direction because of the shoulder formed by the wooden rings. From the flow pictures with three amounts of flare in Fig. 6, it will be seen that the essential characteristics of the flow are not affected by the flare. The energy ratio of the tunnel is slightly affected, it being about 6% higher with all layers on than with all removed.

Bleeder Holes in Exit Cone

To correct for spilling, holes are sometimes put in the bell of the exit cone, allowing some of the air to go back into the experiment chamber. With cones A and D in use, and a row of thirty 1/2 inch holes drilled at the section having the highest static pressure (found by survey to be 1-1/2 inches from mouth of bell on inside wall), no reduction of the currents in the experiment chamber is noticeable. There is less spilling in front of the bell but considerable air comes through the holes at high velocity. With a second and third row of holes drilled 3/4 inch to the front and rear of the first row, the same effect is obtained to a more pronounced degree. There is still no reduction of movement in the experiment chamber but more air comes from the holes and less from in front of the bell. No change in the flow can be noticed, but the energy ratio falls off as holes are added. This amounts to about 11% less with the three rows of holes than without holes. It is possible that with certain peculiar installations the flow can be improved by the use of bleeder holes, but in general they seem to have very little effect.

Proportioning Cones to Eliminate Spilling

From an inspection of the test results as a whole it is evident that cones can be designed to have no appreciable spilling. It is also evident that the exit cone should be larger than the entrance cone in order to take in the spreading or diverging boundary air at the periphery of the main jet, and that the farther it is from the entrance cone the larger it must be to take in all of this spreading air. The following is a rough empirical formula obtained from a consideration of the test results, for determining the minimum exit cone diameter that will give no appreciable spilling:

$$D = d + .18\ h$$

where D = diameter of exit cone at throat

d = diameter of entrance cone

h = distance from mouth of entrance cone to throat of exit cone.

This equation is for cones similar to the experimental ones of Fig. 2, although the exit cones may have somewhat less flare than those in the figure. If a cylindrical extension is put on the entrance cone the angle of divergence of the slow turbulent boundary layer air is less and the exit cone can be made slightly smaller without danger of spilling the air into the experiment chamber.

Conclusions

The flow in open jet tunnels is essentially the same for all cones within the range tested, regardless of shape, relative size, distance between cones, amount of flare on exit cone, or holes in flare of exit cone. The jet has a core of uniform velocity and direction having for these cones about 85% of the diameter of the entrance cone at its mouth, and diminishing uniformly with increasing length at an included angle of 9°. Outside of this central core is a boundary layer of somewhat turbulent air ranging in velocity from that of the jet to zero, and increasing in thickness with the length of the jet.

Spilling of air around the bell of the exit cone causing undesirable currents in the experiment chamber is increased as the distance between the cones is made greater, and as the size of the exit cone is reduced with respect to the entrance cone. A slight amount of flare on the exit cone helps reduce the spilling, but additional flare has no greater effect. An approximate formula is given for the design of cones having no appreciable spilling.

Additional tests of this nature will be made with objects such as airfoils and model airplanes in the jets.

References

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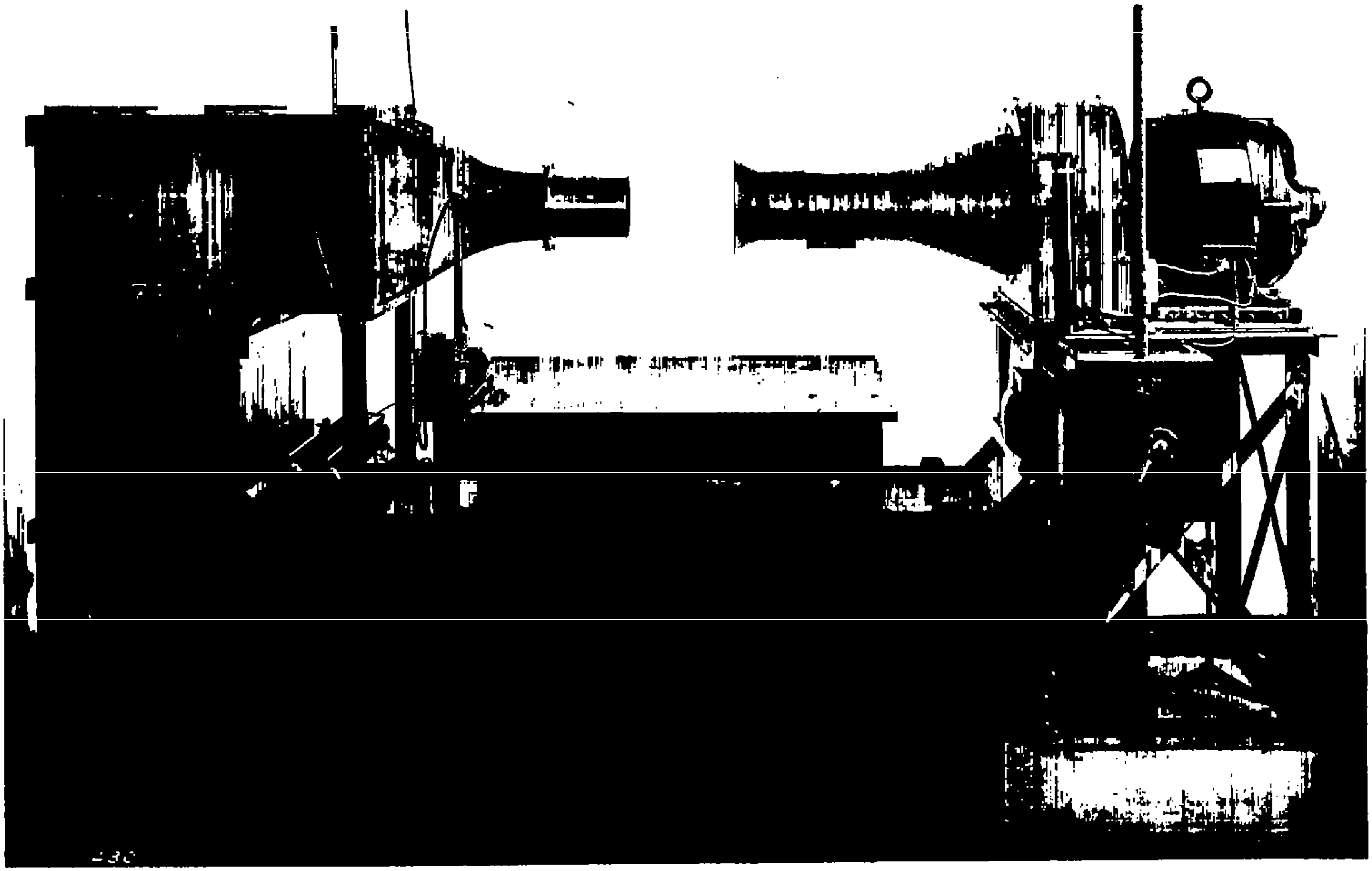

Fig.1. N.A.C.A. 6" Wind tunnel with its standard cones.

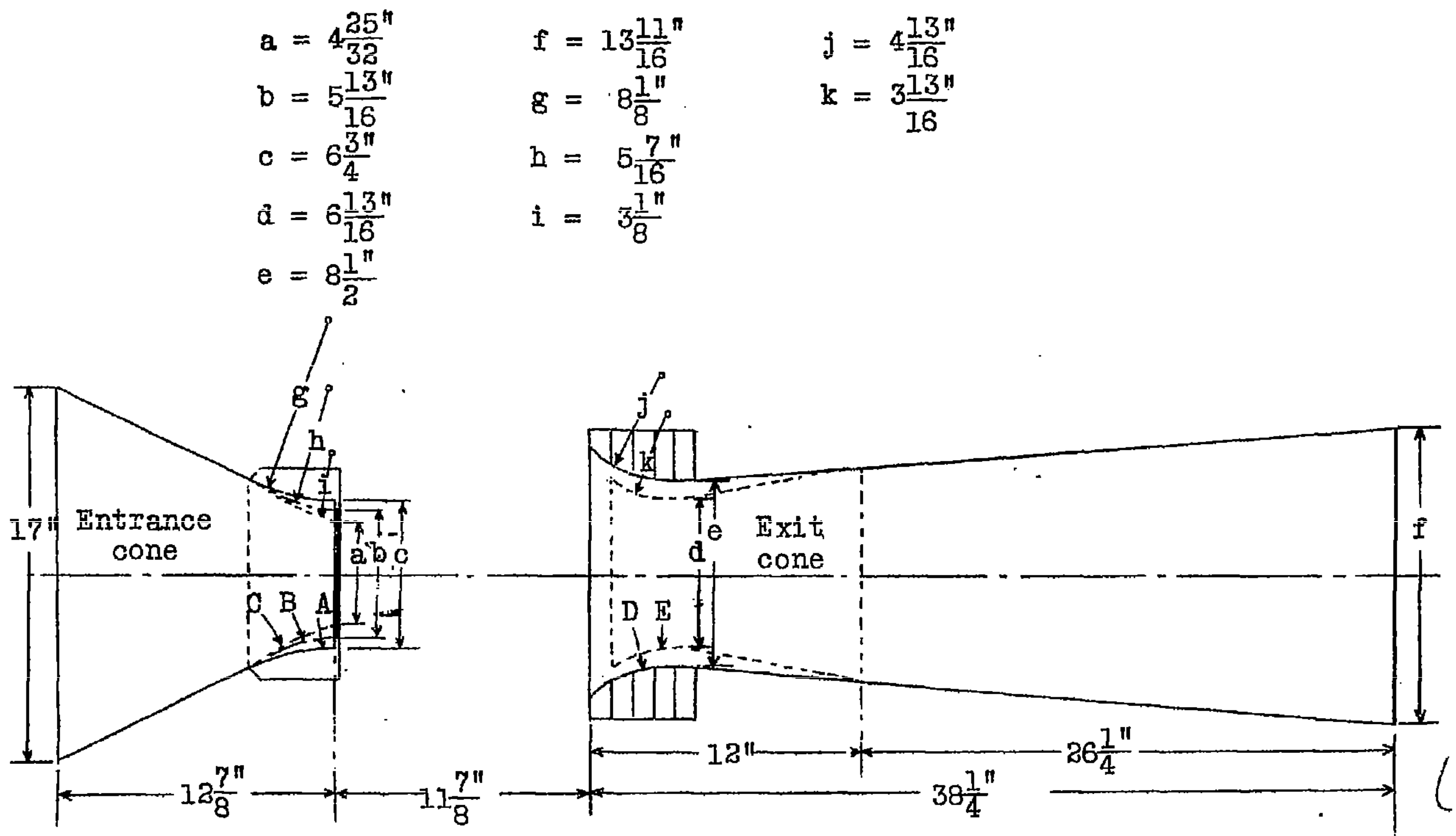

Fig.2 Diagrammatic sketch of experimental cones.

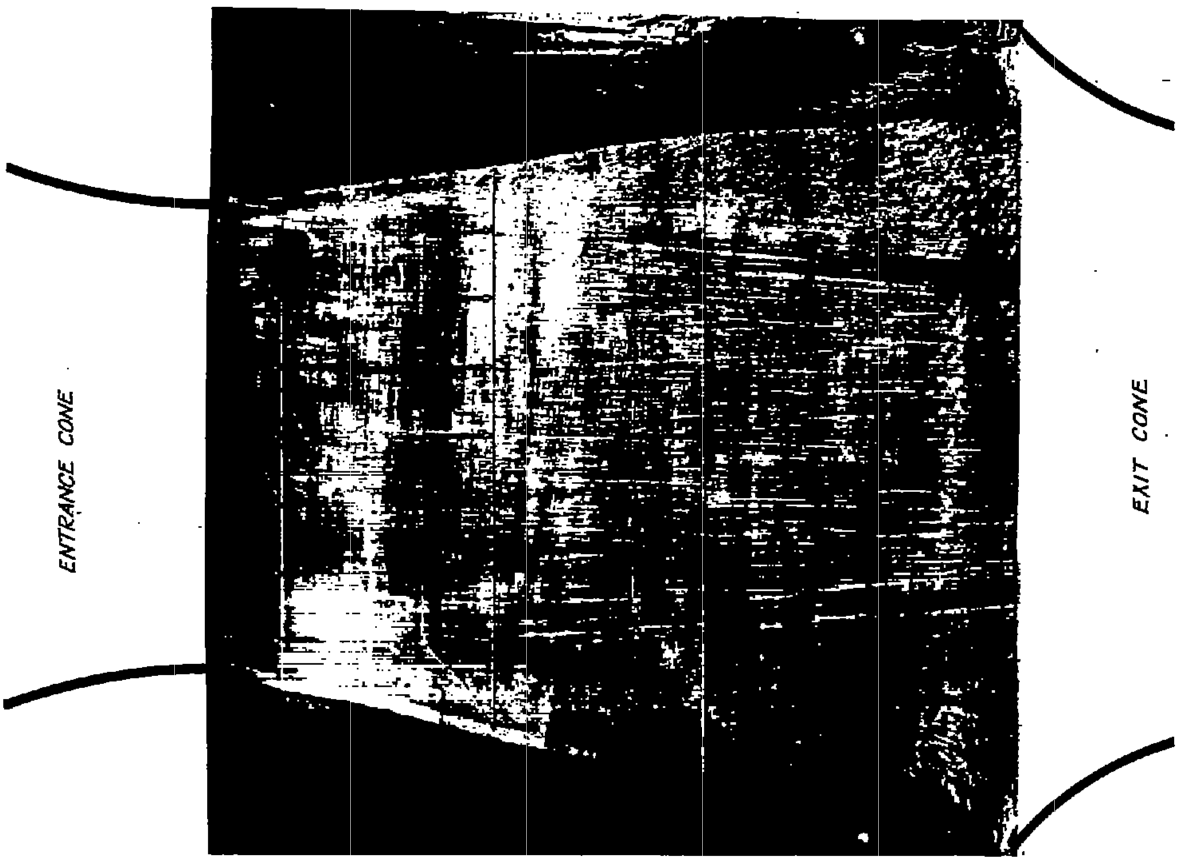

Fig. 3 Typical picture of flow in open jet tunnel with diagrams of velocity and direction superimposed.

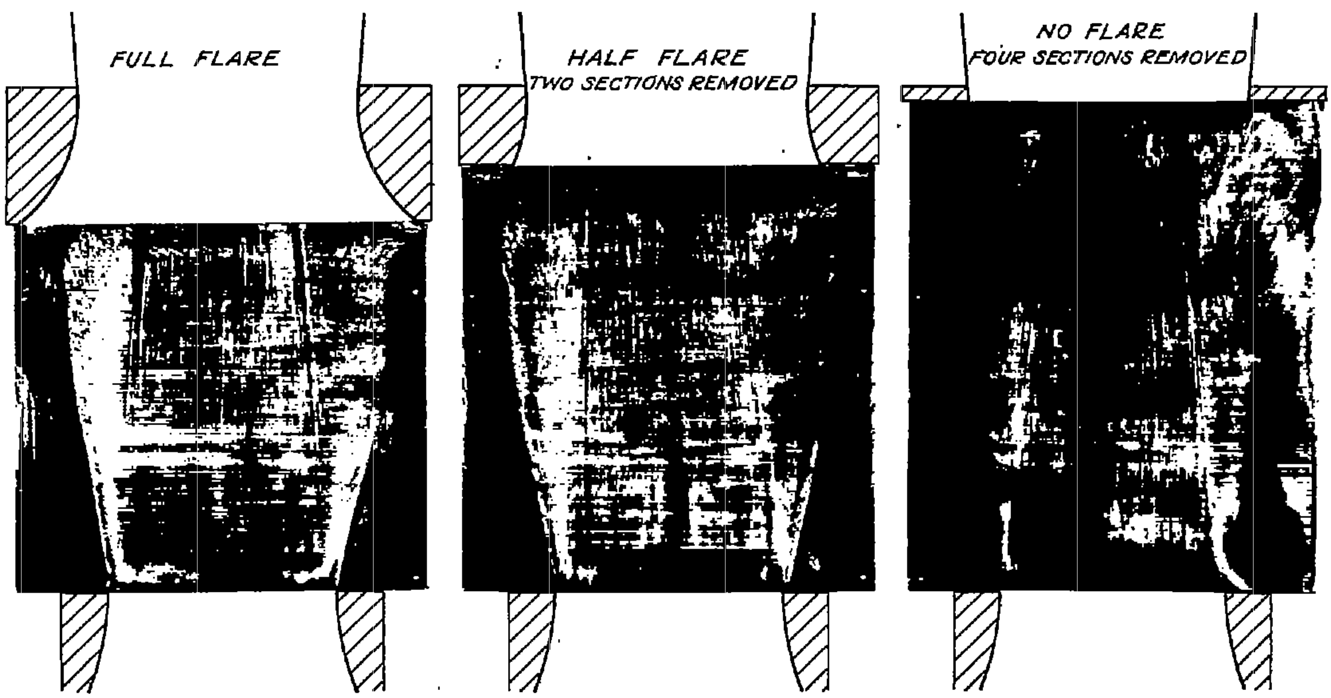

Fig. 6 Flow pictures with various amounts of flare on exit cones.

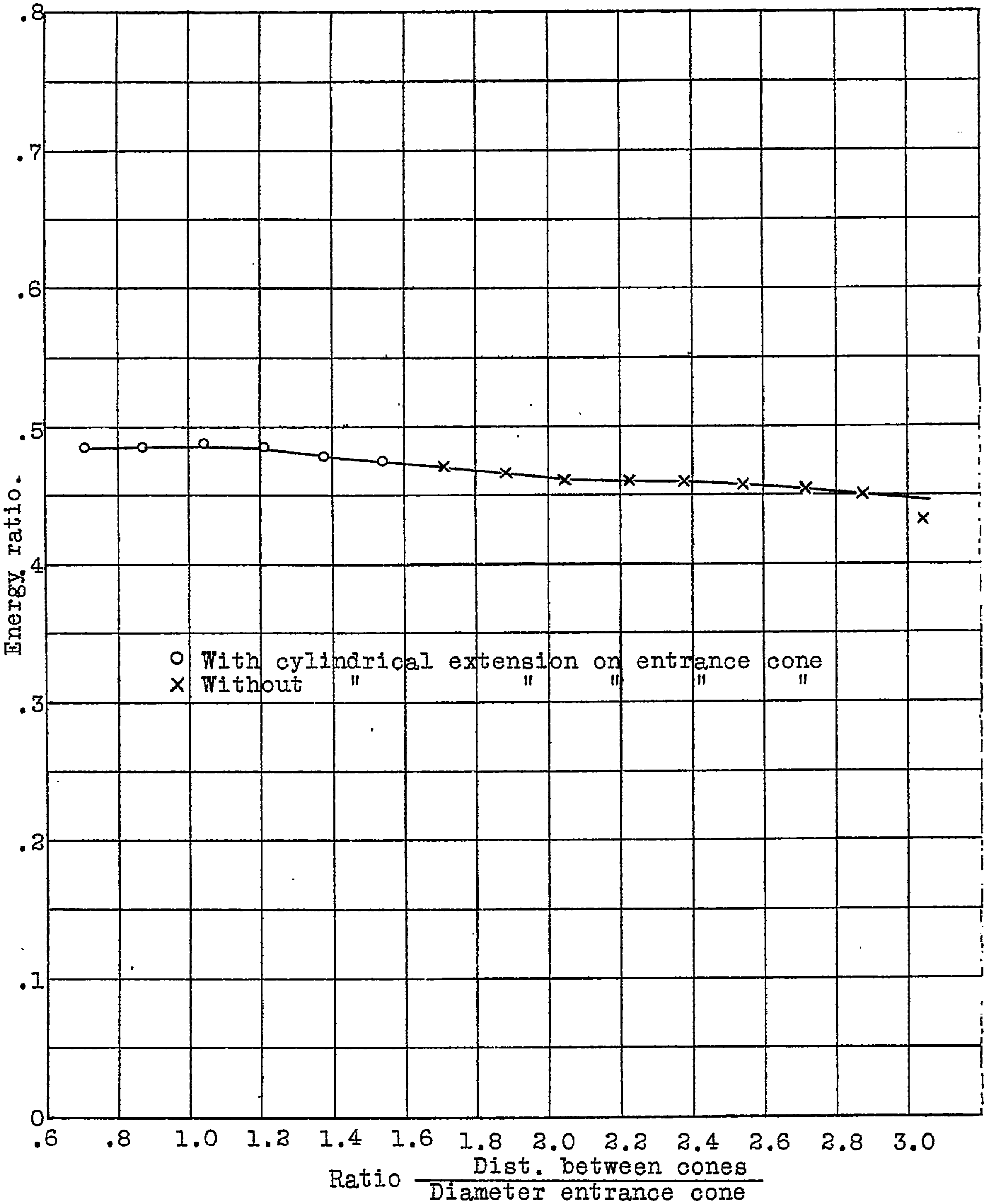

Fig.4 Energy ratio vs. distance between cones.

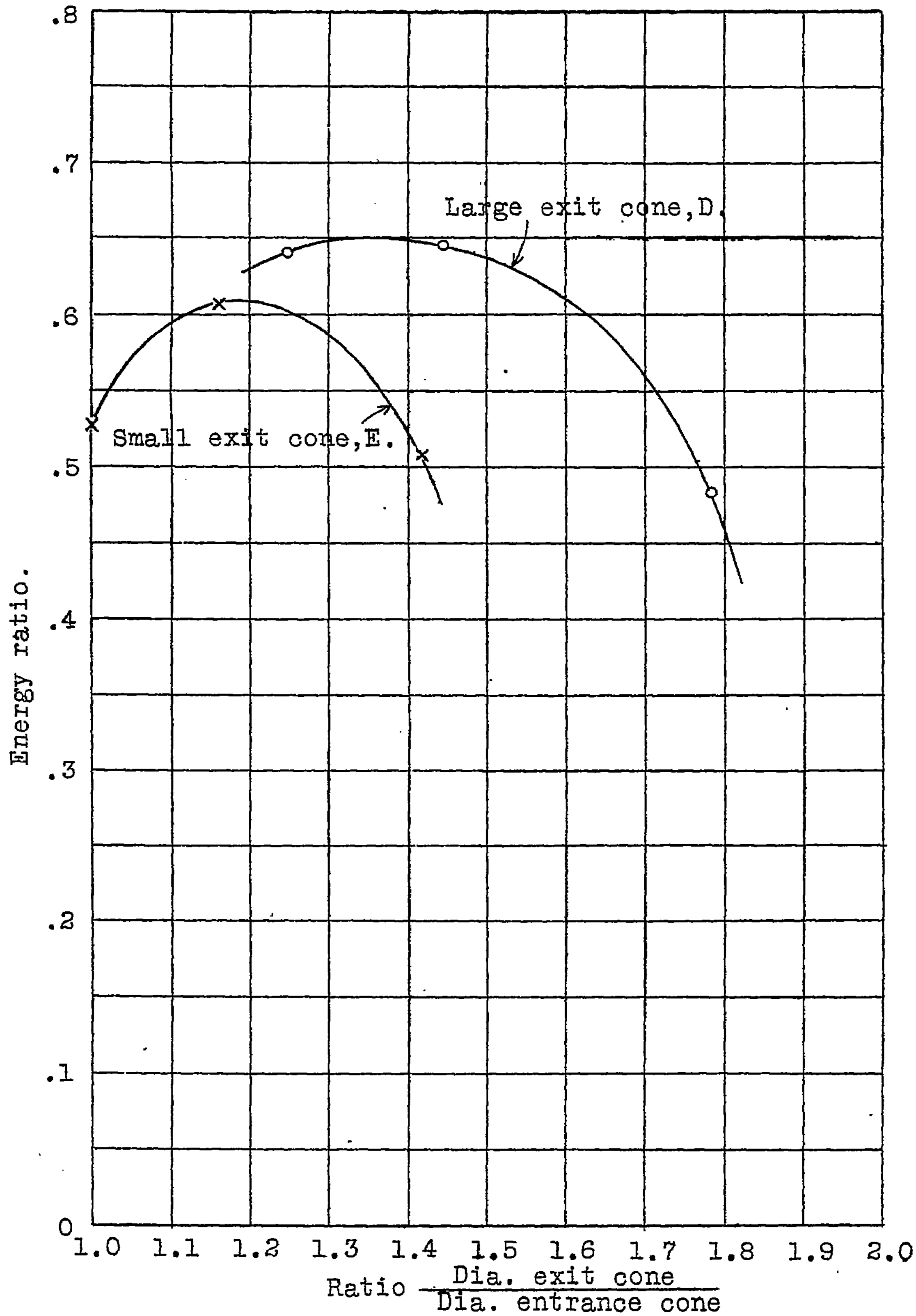

Fig.5 Energy ratio vs. relative size of entrance and exit cones.